

Transformation of Physics Learning Approaches in the Digital Era: A Systematic Literature Study on Curriculum Adaptation and Innovation in Vocational Education

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Abstract - Vocational education institutions in Indonesia face growing pressure to realign physics learning with the demands of Industry 4.0, yet a comprehensive synthesis of how digital curriculum adaptation occurs in this specific context remains limited. This study aims to examine patterns of digital transformation in physics learning approaches, analyze responsive curriculum adaptation strategies, evaluate implemented digital innovations, and formulate strategic recommendations for vocational physics education in Indonesia. A qualitative library research method was employed, with data collected from academic publications indexed in Google Scholar and SINTA, spanning the period 2020–2024. Articles were selected based on inclusion criteria covering relevance to digital physics learning, vocational education context, and publication quality, resulting in ten studies subjected to content analysis and source triangulation. Findings indicate that technologies such as HTML5-based digital comics, STEM gamification, and Arduino microcontroller-based teaching aids have demonstrably improved student engagement and academic outcomes. Responsive curriculum adaptation requires systematic integration of problem-based learning and project-based learning supported by digital technology. Implementation gaps persist between ideal conditions and actual practice, necessitating strategic interventions in educator professional development, industry-academia partnerships, and technology infrastructure investment. This study contributes a holistic analytical framework for understanding the interrelation between technological innovation, curriculum adaptation, and learning outcomes in Indonesian vocational education.

Keywords: digital physics learning; vocational education; curriculum transformation; Industry 4.0; TPACK

INTRODUCTION

The development of Industry 4.0 has driven significant changes in physics learning methodologies within vocational education institutions. The digitalization of learning demands a shift from conventional approaches toward sustainable technology integration, while simultaneously redefining how scientific knowledge, particularly physics, is delivered in vocational contexts oriented toward industrial readiness.

The theoretical foundation of this transformation can be understood through several complementary conceptual frameworks. Vygotsky's social constructivism theory emphasizes that optimal learning occurs through

collaborative interactions mediated by technology as cultural tools (Yani, 2023). In digital physics learning, this principle is manifested through virtual simulations, digital laboratories, and interactive learning platforms. The Technology Acceptance Model (TAM), developed by Davis, highlights perceived usefulness and perceived ease of use as the primary determinants of educational technology adoption. Meanwhile, the Technological Pedagogical Content Knowledge (TPACK) framework proposed by Mishra and Koehler provides a systemic foundation for coherently integrating physics content knowledge, pedagogy, and technology (Mayer & Girwidz, 2019).

Nevertheless, the transformation of physics learning in vocational education still faces various practical challenges. Disparities in technological access among institutions, limited digital competence among educators, and the misalignment between traditional curricula and industrial demands remain unresolved systematically. The heterogeneity of technological infrastructure creates significant digital gaps, while resistance to the shift from teacher-centered models toward technology-based student-centered learning continues to pose a structural challenge (Mayer & Girwidz, 2019).

A review of the literature reveals two major research gaps that have not been adequately addressed. First, there is a lack of systematic synthesis regarding the effectiveness of digital physics curriculum transformation within the specific context of Indonesian vocational education. Second, there is insufficient research exploring comprehensive strategies to overcome barriers in implementing learning technologies across diverse institutional settings. Previous studies have tended to be partial in nature and have not integrated technological, pedagogical, and curricular dimensions into a unified analytical framework (Fadhilah, 2023; Subroto et al., 2023).

Based on the identification of these gaps, this study aims to: (1) identify patterns of transformation in physics learning approaches within the context of vocational education digitalization; (2) analyze physics curriculum adaptation strategies responsive to the demands of Industry 4.0; (3) evaluate innovations in digital physics learning implemented in vocational education; and (4) formulate strategic recommendations for optimizing sustainable digital physics learning transformation in Indonesian vocational education.

LITERATURE REVIEW

The transformation of physics learning in the digital era has become a fundamental paradigm in the development of vocational education, particularly in the context of curriculum adaptation and the implementation of learning technologies that are responsive to the demands of Industry 4.0. Vocational education requires learning approaches that are not only oriented toward mastering theoretical concepts but also toward practical applications relevant to the technical competencies needed in the workplace. Febriani et al. (2020) explored the development of a digital physics comic based on Hypertext Markup Language (HTML5) as a learning medium integrating interactive visualization with applied physics content. The implementation of HTML5 technology in vocational education demonstrated strong feasibility based on expert validation and received positive responses from vocational students. The significance of this study lies in the ability of HTML5 technology to present applied physics content through simulations closely resembling real industrial conditions, which theoretically aligns with the principles of multimedia learning theory emphasizing the integration of visual and textual elements in competency-based learning.

The review of relevant literature is organized into three main themes: (a) digital learning media in vocational physics, (b) STEM and gamification approaches, and (c) educator competencies and curriculum adaptation.

a. Digital Learning Media in Vocational Physics

Febriani et al. (2020) examined the development of an HTML5-based digital physics comic as an interactive learning medium. The study demonstrated that integrating visual and textual elements in

digital formats can effectively present applied physics content, as indicated by expert validation results showing good feasibility and positive student responses. The strength of this study lies in its relevance to multimedia learning theory principles; however, its sample was limited to a single institution, thus requiring further investigation regarding the generalizability of its findings.

Meanwhile, Masyruhan et al. (2020) developed a Hooke's Law teaching aid based on an Arduino microcontroller as a vocational physics learning medium. The device achieved high accuracy in laboratory testing and was deemed feasible by both material and media experts. Compared to digital comics, this innovation offers a more authentic experimental dimension because it allows students to interact directly with physical devices simulating real industrial conditions. However, its limitations include relatively higher production costs and the need for supporting infrastructure (Masyruhan et al., 2020).

Fuadi et al. (2021) developed digital student worksheets (LKPD) that demonstrated very high validity, excellent feasibility, and optimal readability. Unlike the two previous studies, the digital worksheets were specifically designed to support distance learning, thereby providing greater accessibility and flexibility. Collectively, these three studies indicate that the diversification of digital media can address the heterogeneous learning needs of vocational students.

b. STEM and Gamification Approaches

Mahendra et al. (2023) investigated the implementation of gamification in STEM-based physics learning to prepare students for Industry 5.0. The results showed significant improvements in learning outcomes and optimal effectiveness in

developing hands-on experience and problem-solving skills. One major advantage of this approach is its ability to intrinsically motivate students, in line with constructivist learning theory. However, the study did not explore the long-term impact on graduates' workplace competencies.

Viyanti et al. (2021) conducted a needs analysis regarding the development of STEM-based physics learning strategies in the digital era. Their findings revealed that lecturers' understanding of STEM strategies remained relatively low and that learning materials had not yet accommodated diverse student learning styles optimally. Unlike Mahendra et al. (2023), which focused on evaluating innovation, the study by Viyanti et al. (2021) emphasized the gap between ideal conditions and actual practices, making the two studies complementary in understanding the landscape of STEM implementation in vocational education.

c. Educator Competencies and Curriculum Adaptation

Yusro (2022) explored the adaptability and creativity of prospective physics teachers in responding to digital learning transformation. The study emphasized the urgency of mastering Information and Communication Technology (ICT) and critical thinking skills during teacher education. Its theoretical contribution lies in highlighting TPACK as a framework for educators' professional development. However, the study was descriptive in nature and did not provide strong empirical evidence regarding the effectiveness of training interventions.

Irawati et al. (2022) and Suryati et al. (2023) examined the philosophical dimensions of curriculum adaptation, particularly the relevance of Ki Hajar Dewantara's educational philosophy and the impact of the Merdeka Curriculum from a

constructivist perspective. Both studies reinforced the argument that technological innovation should always be integrated with the humanistic values of education. Ubihatun et al. (2024) added a perspective on structural challenges by identifying curriculum rigidity and resistance to change as the primary barriers that still need to be addressed.

Overall, the synthesis of these ten studies indicates that the transformation of vocational physics learning in the digital era faces multidimensional challenges. Digital media innovation and gamification have proven effective in increasing student engagement; however, gaps in educator competencies and curriculum flexibility remain the main limiting factors that require systematic attention.

RESEARCH METHOD

This study employed a qualitative approach using a library research method oriented toward systematic literature synthesis. Data collection was conducted through searches in two major databases, namely Google Scholar and SINTA (Science and Technology Index), using consistently defined keywords: “digital physics learning,” “vocational education,” “curriculum transformation,” “physics learning media innovation,” and “vocational STEM.”

Inclusion and Exclusion Criteria

The articles were selected based on the following inclusion criteria: (1) published between 2020 and 2024; (2) discussing physics learning, science learning media innovation, or curriculum adaptation within the context of vocational education or equivalent settings; (3) employing clear and verifiable research methods; and (4) available in full-text format. Articles were excluded if they: (1) were not directly related

to physics or vocational contexts; (2) were duplicates of studies already included; or (3) did not meet the minimum publication quality standards.

Selection Process

The selection process was conducted in stages following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) principles. During the identification stage, 47 articles were obtained from the initial search results. After screening the titles and abstracts, 21 relevant articles remained. Subsequently, following full-text review and the strict application of inclusion and exclusion criteria, 10 final articles were selected as the analytical corpus for this study.

Data Analysis

Data analysis employed content analysis through three stages: (1) open coding, which involved identifying initial themes from each article; (2) axial coding, which involved grouping themes into broader categories; and (3) selective coding, which involved constructing a synthesis narrative that coherently connected the categories. Data validity was strengthened through source triangulation by comparing findings from various studies to verify the consistency of the identified patterns (Arianto, 2024).

RESULTS AND DISCUSSION

Patterns of Transformation in Physics Learning Approaches within the Digitalization of Vocational Education

The analysis of the ten reviewed studies revealed three dominant patterns in the transformation of digital physics learning within vocational education. First, there has been a shift from conventional media toward interactive digital-based media. Febriani et al. (2020) demonstrated that HTML5-based digital comics successfully improved the

accessibility of complex physics content through interactive visualization, with a high level of student acceptance. This pattern indicates that content digitalization is not merely a change in format, but rather a restructuring of how students interact with physics materials.

Second, there is the integration of physical technology into experimental learning. Masyruhan et al. (2020) showed that Arduino microcontroller-based teaching aids were capable of providing authentic learning experiences, characterized by high accuracy and very positive student responses. This pattern is particularly relevant to vocational education because it bridges theoretical understanding with direct industrial applications.

Third, the role of educators has shifted from knowledge transmitters to facilitators of technology-based learning. Yusro (2022) identified that the creativity and adaptability of physics teachers within digital environments are crucial determinants of successful learning transformation. These findings indicate that technological transformation cannot succeed without a parallel transformation in educators' competencies.

Overall, these patterns demonstrate a systemic shift from a teacher-centered paradigm toward a more dynamic, collaborative, and industry competency-based learning ecosystem.

Strategies for Adapting the Physics Curriculum to Industrial Demands

Viyanti et al. (2021) identified that lecturers' knowledge of STEM-based physics learning strategies that facilitate 21st-century skills still requires significant improvement. In addition, learning materials in textbooks and vocational modules have not optimally accommodated the diversity of students' learning styles. These findings

indicate an urgent need for curriculum reconstruction that is more evidence-based and competency-oriented.

Suryati et al. (2023) reported the positive impact of the Merdeka Curriculum on the development of students' independent thinking skills. The implementation of problem-based learning and project-based learning within this curriculum aligns with the philosophy of constructivism, in which students are encouraged to actively construct knowledge through various available digital media. This demonstrates that top-down curriculum reform can produce positive outcomes when supported by appropriate pedagogical implementation.

However, Ubihatun et al. (2024) emphasized that curriculum rigidity and resistance to change remain significant structural barriers. Effective curriculum adaptation requires continuous alignment with dynamic industrial needs, rather than merely updating formal curriculum documents. Irawati et al. (2022) reinforced this perspective by asserting that curriculum innovation must preserve the humanistic dimensions of education by integrating the pedagogical principles of Ki Hajar Dewantara, ensuring that technology functions as a tool rather than the ultimate goal of learning.

Evaluation of Digital Physics Learning Innovations

Among the ten analyzed studies, all evaluated innovations demonstrated positive impacts on student engagement and learning outcomes, although to varying degrees. STEM gamification (Mahendra et al., 2023) showed the most measurable and consistent improvements in learning outcomes at both junior and senior secondary education levels. Digital student worksheets (Fuadi et al., 2021) excelled in accessibility and flexibility, particularly within distance

learning contexts. Meanwhile, Arduino-based teaching aids (Masyruhan et al., 2020) stood out in providing authentic experimental experiences relevant to industrial standards.

Collectively, these findings indicate that no single approach can be considered universally effective; rather, the effectiveness of an innovation depends on institutional contexts, student characteristics, and intended learning objectives. This underscores the importance of adopting flexible and contextual approaches when selecting learning innovations for vocational education. Rahmawati et al. (2025) further supported these findings by demonstrating that Android-based learning media significantly improved students' critical thinking skills in physics.

Strategic Recommendations

Based on the overall synthesis of the literature, five strategic recommendations are proposed for optimizing the transformation of digital physics learning in Indonesian vocational education. First, there is a need for structured and sustainable professional development programs for educators, emphasizing TPACK mastery, digital literacy, and adaptive pedagogy (Yusro, 2022). Second, curriculum frameworks should be reconstructed by synergistically integrating STEM approaches, problem-based learning, and project-based learning (Viyanti et al., 2021). Third, partnerships between vocational institutions and industry should be strengthened to ensure curriculum relevance and graduate employability (Ubihatun et al., 2024). Fourth, investment in learning technology infrastructure should be accompanied by technical support and sustainable maintenance systems (Masyruhan et al., 2020). Fifth, evaluation

mechanisms involving multi-stakeholder feedback, including students, educators, and industry partners, should be implemented to ensure the sustainability of the transformation process (Irawati et al., 2022).

CONCLUSION

This study reveals that the transformation of physics learning in vocational education during the digital era is characterized by three main patterns: the diversification of interactive learning media, the integration of experimental technologies, and the shifting role of educators. Innovations such as HTML5-based digital comics, STEM gamification, and Arduino-based teaching aids have proven effective in enhancing student engagement and academic achievement. Responsive curriculum adaptation requires comprehensive reconstruction that synergistically integrates STEM approaches, problem-based learning, and project-based learning.

From a theoretical perspective, this study contributes to the development of a holistic analytical framework that integrates technological, pedagogical, and curricular dimensions in understanding the transformation of vocational physics learning. Practically, the findings provide a foundation for policymakers, vocational education administrators, and educators to design contextualized and sustainable implementation strategies. Future research is recommended to employ empirical approaches with broader samples to strengthen the validity of the findings across diverse institutional contexts.

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